

# Decreasing nitrate-N loads to coastal ecosystems with innovative drainage management strategies in agricultural landscapes: An experimental approach

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## ABSTRACT

Innovative controlled drainage strategies in agricultural ditches such as spatially orientated low-grade weirs show promise to significantly improve nutrient (e.g., nitrate,  $\text{NO}_3^-$ -N) reductions by expanding the area available for biogeochemical transformations, as well as providing multiple sites for runoff retention. The overall objective of this study was to identify the contributions made by low-grade weirs to source  $\text{NO}_3^-$ -N concentrations and loads to downstream coastal ecosystems. This objective was achieved by assessing, from an experimental standpoint, the effectiveness of weirs in reducing  $\text{NO}_3^-$ -N concentrations and loads in replicated ditch systems in Jonesboro AR. Overall  $\text{NO}_3^-$ -N load reduction rates were approximately  $2250 \pm 718$  and  $1935 \pm 452$  mg/h for ditches with and without weirs, respectively, resulting in mean percent  $\text{NO}_3^-$ -N load reductions of  $79 \pm 7.5$  and  $73 \pm 9\%$  for ditches with and without weirs, respectively. Although  $\text{NO}_3^-$ -N concentration reductions were substantial in both systems, overall, for the duration of the experiment no significant treatment effect was detected. A stepwise linear regression and repeated measures ANOVA analyzed the relationship of time  $\times$  treatment on nitrate concentration and load in ditch effluents. The regression model explained 31.1% of the variance in  $\text{NO}_3^-$ -N concentration, which indicated a highly significant relationship between  $\text{NO}_3^-$ -N concentration and time  $\times$  treatment ( $F = 31.9$ ,  $p < 0.001$ ).  $\text{NO}_3^-$ -N reductions were significantly higher in weir treatments based on time ( $t = 120$  min;  $F = 3.25$ ;  $p = 0.042$ ) as compared to systems without weirs. Low-grade weirs show promise in improving nutrient reductions in agricultural drainage ditches, by increasing residence time and reducing on a time step basis, outflow concentrations and loads to downstream systems.

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## 1. Introduction

Global population growth will necessitate agricultural expansion within the next 50 years, so much so that food and fiber demands will play a significant role in global environmental change (Tilman et al., 2002). Agricultural production is ubiquitous in its use of inorganic fertilizers to increase yields, which results often in high loads of nutrients delivered from agricultural soils to adjacent receiving waters (Donner, 2003). Environmental issues surrounding nutrient contamination, specifically nitrate-N ( $\text{NO}_3^-$ -N) are primarily linked to its impact on surface water eutrophication. However, causes of coastal ecosystem degradation and eutrophication are rooted in nutrient loads derived from non-point sources (e.g., agricultural) high in the associated catchments and watersheds. The relevance of this issue is no more prevalent than in coastal areas of Mississippi and Alabama in the Gulf of Mexico.

Nitrogen is probably the most complex element to characterize in aquatic biogeochemical processes (Keeney, 1973). Nitrogen as a non-point source pollutant from crop fields, typically applied as urea, occurs predominantly in the inorganic form ( $\text{NH}_4^+$ ). The dominant aqueous N species of  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ -N, nitrite ( $\text{NO}_2^-$ ), and dissolved organic N, undergo simultaneous complex interactions and transformations of mineralization, immobilization, nitrification, denitrification, and assimilation at variable spatial and temporal scales (Braskerud, 2002; Klopatek, 1978; Ryden et al., 1984). Net N concentrations in aquatic systems are a combination of these processes as well as the rate of decomposition and the rate of sedimentation (Keeney, 1973).

Biogeochemical properties of N can be manipulated through management. By managing primary aquatic systems associated with agricultural N sources, scientists and managers can greatly increase reduction effectiveness. Studies have shown managed drainage ditch systems in agricultural landscapes will result in decreased loads of nitrogen (Cooper et al., 2002, 2004; Kröger et al., 2007) entering adjacent aquatic systems. Agricultural drainage ditches are integral components and ubiquitous features of the agricultural landscape and act as major conduits of surface and

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subsurface flow N from agricultural lands to receiving waters. Drainage ditches are wetlands that are the forgotten links between agricultural fields and receiving waters (Moore et al., 2001). They possess hydric soils, support a diverse community of hydrophytes, and are subject to the unpredictable changes in soil saturation as a result of hydrological variability. Controlled drainage practices such as flashboard risers (Evans et al., 1992, 1995; Gilliam and Skaggs, 1986; Gilliam et al., 1979), controlled sub-irrigation (Bonaiti and Borin, 2010; Borin et al., 2001) and low-grade weirs (Kröger et al., 2008, 2011) within ditches have been proposed as best management practices primarily aimed at reducing nutrient concentrations and loads in ditches reaching receiving waters by reducing total outflows. A commonly used practice for controlled drainage involves the use of a variable height riser in the drain or ditch outlet (Lalonde et al., 1996; Madramootoo et al., 1993; Skaggs and Gilliam, 1981). This concept relies on the ability to control drainage intensity by determining the height of the riser and thus, control volume of outflow and load of solutes (Wesström et al., 2001). Kröger et al. (2011) documented that there were no statistically significant differences in N and P concentrations or loads when risers were compared to low-grade weirs. Nevertheless, both technologies increased hydraulic residence time and both significantly declined influent nutrient concentrations and loads (67–98% N and P).

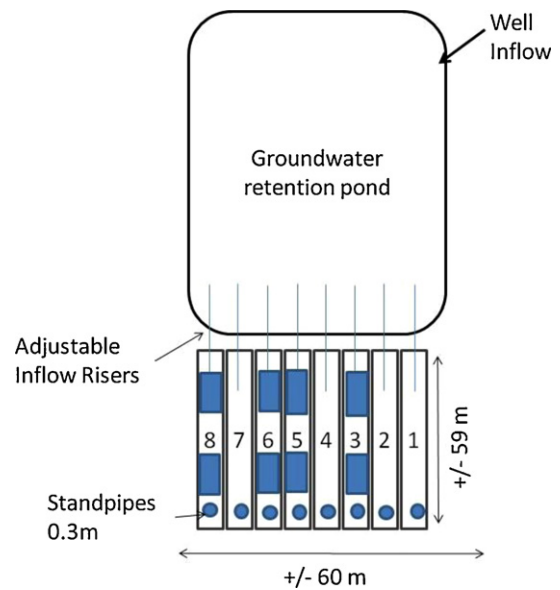
Taking into consideration that certain surface drainage ditches are hundreds of meters long with variable slopes, the installation of low-grade weirs (henceforth referred to as weirs) within the drainage ditch at multiple spatial locations within the agricultural landscape would create continuous stepwise increase of water levels that improve retention and control drainage. This innovative concept provides drainage management on an annual and spatially graduated basis, rather than a single slotted riser occurring during the dormant season. Spatial allocation of weirs has some significant theoretical improvements over conventional drainage ditch systems. The very important service of first flush capture of non-point source contaminants would occur at multiple locations and entry points along the drainage ditch, rather than just at the outflow. Multiple weirs will increase chemical residence time within each drainage ditch, and provide multiple sites for magnified microbial transformations, nutrient adsorption, and improved sedimentation. Spatially orientated weirs show promise to significantly improve N reductions by expanding and creating synergistic aerobic and anaerobic soil conditions through decreased flow rates and increased water levels and volumes.

The current study, using an experimental outdoors setup, aimed to investigate changes in  $\text{NO}_3^-$ -N load and concentration as a result of controlled drainage practices (i.e. use of weirs) in artificially created drainage ditches.  $\text{NO}_3^-$ -N reductions were tested by using replicated ditch systems (1.8 m (width)  $\times$  58.7 m (length)  $\times$  0.3 m (diameter)) that compared weired versus traditional drainage systems (i.e., without weirs) at Arkansas State University (ASU) agricultural research facility in Jonesboro, Arkansas.

## 2. Materials and methods

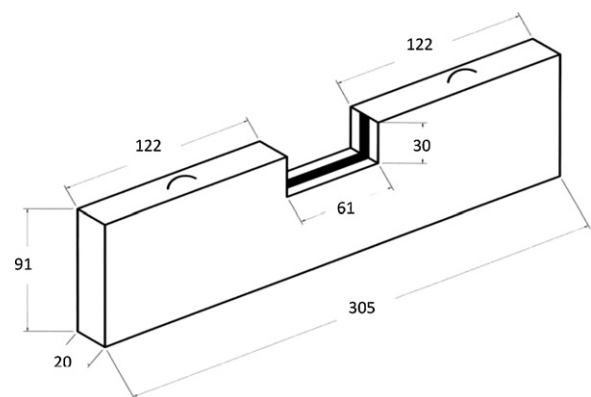
### 2.1. Experimental setup

The ASU agricultural research facility (35°50'32.92"N, 90°42'15.87"W) is located approximately 5 km west of the Arkansas State University campus in Jonesboro, AR. This site contains eight drainage ditches that were constructed in 2006. Each ditch was hydro seeded in 2007 and 2008 and now consists of well established vegetative communities (*Typha latifolia* L.). Ditches have a mean width and length of 1.8 m and 58.7 m, respectively, with 0.1% slopes along their length.



**Fig. 1.** Replicated drainage system at the agricultural research facility at Arkansas State University, Jonesboro, AR. Eight replicated systems, four of which contained weirs, and four which were drained under conventional methods. Standpipes were lowered on each system to represent summer drainage conditions.

The ASU facility was used to provide an experimental, outdoor, replicated approach to study the  $\text{NO}_3^-$ -N mitigation capabilities of low-grade weirs. Each of the eight ditches contained an independent, adjustable inflow and outflow hydraulic structure (Fig. 1). A groundwater well supplied a large retention pond that contained eight standpipes. Each retention standpipe was attached to ball valves that acted as inflows to each ditch. These valves controlled the flow entering the system. Each ditch also contained standpipes that acted as outflow structures. Each ditch standpipe was turned down to simulate summer drainage conditions. Summer drainage conditions means low water volume in ditches due to the lack of precipitation, and expedient drainage to avoid flooding. Four ditches were randomly chosen to contain weirs (Table 1), and the remaining four were drained conventionally. Each chosen ditch contained two weirs, for a total of eight weirs. Each weir was a prefabricated constructed concrete retention structure (Fig. 2), referred to as a Scurlock Weir®. The height of each gate was determined based on the fall of the ditch. Ditch slopes and weir heights were quantified using a Trimble laser Theodolite unit (Trimble Navigation Limited) with a fixed base station. Ditch widths,



**Fig. 2.** Concrete manufactured "Scurlock Weir"® that was constructed as a low-grade weir. The structure weighs approximately 1272 kg, has a stainless steel C-channel and two rebar loops for ease of installation and removal. Structure dimensions are in cm.

**Table 1**

Hydraulic characteristics for ditch volume, inflow rate, hydraulic residence time (HRT), and QD pump flow for each ditch. Inflow values are represented by the mean of all inflow measurements at each ditch taken over the 8 h sampling period.

	Ditch 1 (NW)	Ditch 2 (NW)	Ditch 3 (W)	Ditch 4 (NW)	Ditch 5 (W)	Ditch 6 (W)	Ditch 7 (NW)	Ditch 8 (W)
Ditch volume (L)	2382	3740	11760	2674	24240	20611	4267	8770
Inflow (L/min)	45.4	47.3	43.2	33.4	60	59.8	34.1	24.3
HRT (h)	0.87	1.32	4.54	1.33	6.73	5.75	2.09	6.01
QD flow (mL/min)	522	543	496	384	690	690	392	280

lengths, and depths were quantified with the use of a meter tape and a meter stick. Trapezoidal ditch channels were measured for width and depth at maximum measured water levels. A total of 45 measurements associated width (maximum water width) and depth (deepest point of the cross-section) were taken longitudinally within each ditch. These measurements were calculated into total ditch water and weir volumes (Table 1). Ditch volume was constant during the experiment. From these calculations, we also determined the  $\text{NO}_3^-$ -N load being discharged from each ditch. Fixed YSI® (Yellow Springs Instruments, Ohio, US) automated data-sondes, recording data every 5 min, were placed in four ditches (two with weirs and two without) to look at potential differences in water quality parameters of dissolved oxygen (mg/L), water temperature ( $^{\circ}\text{C}$ ), pH, specific conductance ( $\mu\text{S}/\text{cm}$ ) and water column oxidation-reduction potential (ORP; mV). Similarly, every hour a handheld, on site calibrated, YSI instrument was used to determine dissolved oxygen, pH, water temperature and specific conductance behind each weir, within each ditch with no-weirs, as well as in the detention pond. Sediments were batch sampled ( $n=3/\text{ditch}$ ) and analyzed for particle size on ground sediment using the hydrometer method of Bouyoucos (1962).

## 2.2. Storm event delivery

A single simulated storm runoff event was introduced to each ditch simultaneously for eight hours. Each ditch was filled to capacity prior to simulation and flow-through had been established for 30 min. Water was supplied from the retention pond throughout the experiment. Inflow rate from the retention pond was measured every hour for each of the eight hours of the experiment (Table 1). A HOBOTM (Onset, Pocasset, MA) water level recorder within the retention pond monitored changes in water level which could be correlated to observed changes in flow through time. Flow was assumed constant, with negligible fluxes as a result of changes in detention basin head pressure during the experiment. Flow rates were determined in triplicate for each ditch for each hour of the experiment, using the bucket method. The bucket method is a simple technique that determines flow with timing the accumulation of water to a known water volume level (15 L bucket). The source of  $\text{NO}_3^-$ -N concentration as an amended slurry was two 2.2 kg bags of Calcium Nitrate ( $\text{Ca}(\text{NO}_3)_2$ ). A mixing chamber contained the 1920 L slurry that was simultaneously amended through flexible Tygon® tubing to each ditch. The slurry was delivered through vinyl tubing by high flow model QD pumps (Fluid Metering Inc., Syosset, NY), individually calibrated for each ditch. Target ditch concentrations for  $\text{NO}_3^-$ -N were 3–4 mg/L, as determined by communications with Natural Resource Conservation Service (NRCS) employees for comparative recorded concentrations in runoff from agriculture in the Delta of Mississippi. Sampling of each ditch occurred at a pre-determined time based on the calculated hydraulic residence time of each ditch (Table 1). Increased sampling frequency occurred on the rising limb of each respective ditches breakthrough curve, with hourly sampling occurring post breakthrough. Samples were collected in 250 mL polyethylene cups (Fisher Scientific, Pittsburgh, PA), immediately placed on ice, and transported back to the Water Quality Laboratory at Mississippi

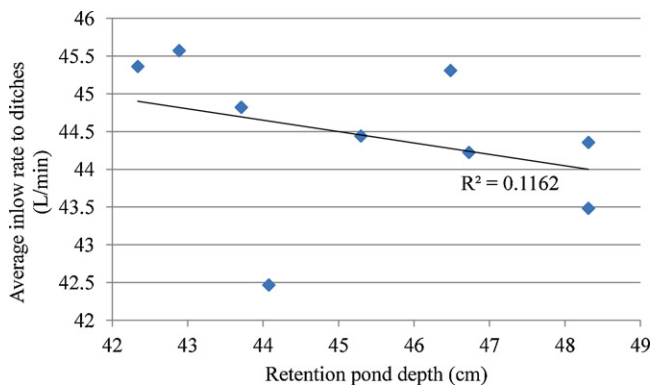
State University for nutrient analysis within 24 h. Samples were stored at  $4^{\circ}\text{C}$  until analysis was completed. Samples were filtered using a pre-washed  $0.45\ \mu\text{m}$  Whatmann Nitrate-Cellulose filter membrane before analysis.  $\text{NO}_3^-$ -N concentrations were determined using the cadmium reduction powder pillow method (APHA, 1998) on 25 ml aliquots. Quality assurance procedures of field/lab (precision) and instrument (accuracy) duplicates provided confidence in concentrations derivations.

## 2.3. Statistical analyses

All statistical analyses were determined using PASW 18, developed by SPSS, Inc. Unless otherwise stated all statistical analyses utilized a two-sample independent *t*-test ( $N=8$ ) and assumed  $\alpha=0.05$ . The influence of unequal variances between treatments was determined using Levene's test for equality of variance and the appropriate *p*-value selected. Shapiro Wilks *W* test was used to test for normality and goodness of fit in the data sets. To determine the effect of weirs on effluent  $\text{NO}_3^-$ -N concentrations over time, a repeated measures analysis was performed on hourly samples. The assumption of sphericity was not met; thus the Greenhouse-Geisser value was calculated to determine significance. A stepwise linear regression was performed to determine the percent variability in  $\text{NO}_3^-$ -N concentration that could be explained by the presence of weirs. Outflow loads were established per replicate system by averaging  $\text{NO}_3^-$ -N concentrations between sampling periods, multiplied by outflow flow volumes and sampling period duration to determine load loss from each respective system for a respective time period.

## 3. Results

Particle size analysis of sediments highlighted that ditch sediments consistently consisted of  $97 \pm 1\%$  silt, with no statistical differences between ditch systems. HOBOTM water level data from the detention basin showed a slight increase in water level throughout the duration of the runoff event ( $\pm 6\text{ cm}$ ). A linear correlation showed no significant statistical change between retention pond water depth and inflow rates through time for the duration of the runoff event (Fig. 3). Mean dissolved oxygen (DO) concentrations ( $F=4.83$ ;  $p=0.01$ ), as well as percent DO saturation ( $F=3.31$ ;  $p=0.04$ ), were statistically different between the retention pond, and ditches with and without weirs. The retention basin had the highest dissolved oxygen ( $10.1 \pm 1.1\text{ mg/L}$ ) concentrations. Systems with weirs, had significantly (unequal variances  $t=2.08$ ;  $p=0.04$ ) lower dissolved oxygen concentrations ( $6.6 \pm 0.3\text{ mg/L}$ ) than systems lacking weirs ( $7.7 \pm 0.5\text{ mg/L}$ ). Other *in situ* water quality variables of pH, water temperature, and conductivity showed no statistical differences ( $p>0.05$ ) between ditch systems. The water volume of ditches with weirs was approximately five times greater than ditches without weirs, approximately 16,335 versus 3265 L ( $p=0.036$ ). Mean hydraulic residence time (HRT) was  $342 \pm 86$  and  $78 \pm 28\text{ min}$  for ditches with and without weirs, respectively. This fourfold difference represents a significant increase in HRT for ditches with weirs ( $p=0.0059$ ).



**Fig. 3.** Linear correlation between water depth in retention pond (cm) and mean inflow rates (L/min) for all ditches, at each hour ( $T=0-8$  h) for the duration of the runoff event.

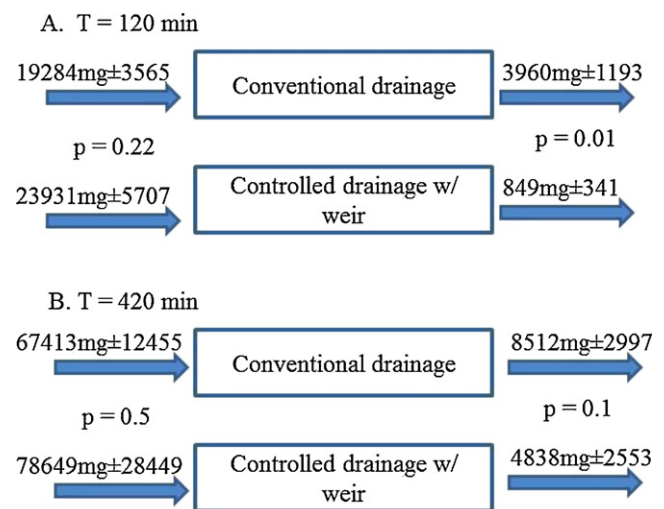
Mean peak  $\text{NO}_3^-$ -N concentrations for ditches without weirs were 0.43 mg/L at 146 min. In ditches with weirs, mean nitrate concentration peaked at 0.31 mg/L at 390 min. When  $\text{NO}_3^-$ -N concentrations measured over the course of the study were averaged for each ditch, no significant treatment effect was evident ( $p=0.382$ ). However, because of lack of independence of samples taken at different times within the ditch, time was not considered in this analysis. A repeated measures analysis revealed a significant time  $\times$  treatment interaction (Greenhouse–Geisser  $F=3.285$ ,  $p=0.042$ ).  $\text{NO}_3^-$ -N concentration was significantly higher in ditches without weirs ( $p=0.001$ ) at  $t=120$  min. The difference in  $\text{NO}_3^-$ -N concentration was gradually attenuated and by  $t=420$  min, the sampling time after the spiked parcel of water would be expected to have reached the outflow in all ditches, concentrations were equal between treatments ( $p=0.910$ ).

$\text{NO}_3^-$ -N load reduction rates were approximately  $2250 \pm 718$  and  $1935 \pm 452$  mg/h for ditches with and without weirs, respectively, resulting in mean  $\text{NO}_3^-$ -N reductions of  $79 \pm 7.5$  and  $73 \pm 9\%$  for ditches with and without weirs, respectively. Although  $\text{NO}_3^-$ -N reductions were substantial in both systems, no significant treatment effect was detected. A stepwise linear regression was performed analyzing the relationship of time  $\times$  treatment on  $\text{NO}_3^-$ -N concentration. This model explained 31.1% of the variance in  $\text{NO}_3^-$ -N concentration, which indicates a highly significant relationship between  $\text{NO}_3^-$ -N and time  $\times$  treatment ( $F=31.9$ ,  $p<0.001$ ). Fig. 4 describes the mass balance of  $\text{NO}_3^-$ -N for the two systems at  $t=120$  and 420 min. Unequal variance  $t$ -tests show statistical differences in mass outflows at  $t=120$  min, but no differences in inflows for each time period and outflows at the end of the experiment.

#### 4. Discussion

The observed differences in DO between the retention pond and ditches may have resulted from differences in measured DO values and inflow values resulting from pond stratification. The pipes used to fill the ditch were slightly lower in the water column than the datasonde, indicating that DO may have been lower. Differences in DO between treatments could be due to increased turbulence in the conventionally drained systems due to higher velocity, or due to higher oxygen depletion in the system containing weirs. It is more likely that the increased HRT of systems with weirs caused oxygen from the water column to be used by organisms in the benthos or soil interstices. While the differences in DO between treatments are statistically significant, these differences may have only a negligible effect on the biological and chemical properties of the system.

Hydrologically, low-grade weirs, whether associated with vegetated drainage ditches or not, increase the overall hydraulic



**Fig. 4.** Mass balance comparison of nitrate-N loads between conventional drainage and controlled drainage with weirs, at 120 min and 420 min. Values are means  $\pm$  S.D.;  $p$  values were derived from unequal variance,  $t$ -tests.

residence and capacity of the system (Kröger et al., 2008). The HRT of ditches without weirs was 78 min, a third of the average HRT for ditches with weirs, indicating potential nutrient differences are likely due to the parcel of water containing the nutrient slug arriving at the outflow earlier in the ditches lacking weirs. However, if the hydraulic capacity of the system was overloaded, and the increased residence time provided by weirs was negated, the study highlighted no statistical differences in concentration or load reductions of  $\text{NO}_3^-$ -N between controlled drainage and conventional drainage. Because the ditches were filled to capacity prior to nutrient amendments, outflow rates of water are assumed to be approximately equal to measured inflow rates. Realistically, outflow rates were lower than inflow due to evapotranspiration. A large percentage of the decreases in  $\text{NO}_3^-$ -N seen in the systems is likely due to dilution of the nutrient slug into water with lower background concentrations. Surprisingly, however, Ditch 8, the controlled-drainage ditch with the lowest volume also had the lowest peak nitrate concentration (0.17 mg/L) and even at this peak concentration, delivered higher reduction rates than the other ditches. Because of its decreased volume, the discharge of this ditch was less than other ditches with weirs, a factor that has been demonstrated as being crucial for improving water quality in stochastic systems (Carleton et al., 2001). The decreased depth in Ditch 8 also coincides with an increased water–sediment and water–macrophyte interface relative to the volume of water moving through the system and may have been one reason the controlled-drainage weirs, with their greater volume did not significantly outperform conventionally drained ditches.

Mass balances calculated for data recorded 420 min after treatment initiation demonstrate that a large percentage of the  $\text{NO}_3^-$ -N entering the system is not present in the effluent. Given the fact that 420 min is approximately 2–10 times the expected retention time for all of the ditches except Ditch 5, dilution of the inflow sample is likely playing little role in this apparent loss of  $\text{NO}_3^-$ -N. The presence of dense vegetation (*T. latifolia*) may have been influential in this response via direct uptake (Peterson and Teal, 1996), or increased water column–sediment interactions (Martin et al., 2003) or increased surface areas for biofilms, such as periphyton (Brix, 1997). While direct organic assimilation of  $\text{NO}_3^-$ -N by *T. latifolia* was unlikely to have influenced outflow concentrations, the presence of periphyton on vegetation can substantially impact nutrients in the water column (Axler and Reuter, 1996). Macrophytes have



also been implicated in facilitating denitrification, which could be another cause of  $\text{NO}_3^-$ -N loss.

Kröger et al. (2011) compared low-grade weirs with traditional controlled drainage strategy of slotted risers. The study highlighted equal water volumes retained by the respective controlled drainage practices, and thus no statistical differences in nutrient concentration or load reductions among controlled drainage treatments. However, all ditch replicates had >80% reductions in  $\text{NO}_3^-$ -N, ammonia-N and total and reactive phosphorus. Increased hydraulic residence is the key variable for providing improved nutrient reductions—specifically  $\text{NO}_3^-$ -N (Dinnes et al., 2002; Drury et al., 1996). When examined on a time step basis with a step-wise linear regression, and repeated measures, systems with weirs decreased outlet  $\text{NO}_3^-$ -N concentrations and loads significantly more than systems without weirs. This difference is attributed to increased residence, and increased dilution effect. Overloading systems past HRT capacity, which theoretically suggests influent and effluent are equal, provides a means to understand the biogeochemical reduction of each system. This study was limited in elucidating this effect, as the experiment did not extend the temporal capacity in weired systems sufficiently to statistically evaluate biogeochemical differences. There is no literature that has disseminated the dilution and biogeochemical effects of nutrient management strategies (i.e., constructed wetlands, controlled drainage) and solely examined biogeochemical reduction capacity of best management practices.

Comparisons between the ASU experimental system and field scale research are needed to verify the significance of these results. Kröger et al. (2007) reported for field ditches farmed under cotton, a 57% reduction in dissolved inorganic N load, with variable  $\text{NO}_3^-$ -N specific concentration reductions between 22 and 61% as a result of hydrological variability. In an analysis of 72 nitrate-dominated surface flow wetlands, Kadlec and Wallace (2009) found a 65% annual median reduction and a 54% annual mean reduction for  $\text{NO}_3^-$ -N. Median inflow values (4 mg/L) were comparable to the current study, while mean (12.8 mg/L) inflow values were approximately four times the values measured within the current study. Verifying experimental scale research with field observed concentrations and loads, as well as verifying field scale nutrient reductions with experimental scale results will enhance our understanding of nutrient reductions within drainage systems with controlled drainage, as well as, provide a verifiable research avenue for future work.

## 5. Conclusion

Agricultural water management is moving towards increasing environmental stewardship while improving nutrient reductions within captured runoff. Controlled drainage with low-grade weirs is a strategy for surface drainage ditches that will increase hydraulic retention capacity, potentially improve conditions for biogeochemical transformations and thus enhance  $\text{NO}_3^-$ -N concentration and load reductions over conventionally drained systems. Future research aims to provide field scaled nutrient concentrations highlighting reductions through low-grade weirs to explain biogeochemical conditions (i.e., redox, pH) associated with these plausible management strategies.

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